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(6) OPTIONAL ELECTRIC METHODS INVESTIGATED AS SUBSTITUTES FOR THE S. G. CONCRETE MIX TESTER

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U. S. NAVAL CIVIL ENGINEERING LABORATORY
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OPTIONAL ELECTRIC METHODS INVESTIGATED AS SUBSTITUTES FOR THE S. G. CONCRETE MIX TESTER

Task No. Y-R007-05-015

Type B

by

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ABSTRACT

The proprietary S. G. Tester previously was found incapable of detecting variations in water-cement ratio as small as ±0.01 (by weight). Accordingly, three optional electric methods were investigated, namely, (a) resistance to alternating current, (b) power loss, and (c) induction conductivity. Cement pastes, representing water-cement ratios (by weight) ranging from 0.40 to 0.60, were used as the media.

The reliability of the 1000-cycle alternating-current resistance method is inferior to that of the direct-current resistance method utilized in the S. G. Concrete Mix Tester. The power loss method and the induction conductivity method do not detect changes in water-cement ratio as satisfactorily as does the S. G. Concrete Mix Tester.

The direct-current resistance method, as exemplified in the proprietary version of the S. G. Tester, is considered the most promising. This electric method can serve satisfactorily in detecting water-cement ratio (by weight) discrepancies within a ±0.05 tolerance.

INTRODUCTION

The possibility of controlling the quality of freshly mixed concrete by employing a portable instrument to detect variations in water-cement ratio (W/C) within a tolerance of ± 0.01 (on a weight basis) has long been a goal in concrete research. This resulted in the initiation, by the Bureau of Yards and Docks, of a research task to ascertain the feasibility of the proprietary apparatus known as the S. G. Concrete Mix Tester and to develop whatever modifications thereof might be desirable.

In accordance with the task instructions the proprietary apparatus was evaluated and the progress of the investigation was documented as an interim report.* It was shown that the proprietary apparatus, which had been designed to operate only as a direct current resistance measuring device, could not be expected to fulfill the requirements specified by the Bureau. Included in that report, in the section entitled Future Plans, were brief descriptions of three other approaches to resolving the task objective. These other electric methods involve measurement of: (a) resistance to 1000-cycle alternating current, (b) power loss, and (c) induction conductivity. Option (a) literally is an extension of the basic principle of the S. G. Tester; options (b) and (c) involve radical departures from the usual probe-type of instrument.

This document is the final report concerning the assigned research task and includes the results of investigations concluded since the issuance of the interim report.

INSTRUMENTATION

Alternating-Current Resistance Method

The 1000-cycle alternating-current apparatus consisted of three units: a Baldwin model N strain indicator having a dial graduated in microinches per inch, a combination of resistive units equipped with multipoint switches, and the probe. The basic circuit, depicted in Figure 1, was a densensitizing resistor network (i.e., a standard Wheatstone bridge equipped with a densensitization network); this incorporated a special null-balance

*U. S. Naval Civil Engineering Laboratory. Technical Note N-420, S. G. Concrete Mix Tester, by William R. Lorman. Port Hueneme, 7 September 1961, 17 pp.

bridge circuit designed so that no current flows in the measuring circuit. The null balance (no current-flow) indicator was substituted for the usual galvanometer. The movable contactor (slide wire resistance) was calibrated in scalar units equivalent to 0.001 ohm per scalar division of the indicator and thus for all practical purposes was a direct-reading instrument. With the two external resistors of the bridge connected in adjacent arms, the internal variable resistance was adjusted to null-balance condition and the difference in voltage between the signal terminals was zero, resulting in no current flow. The calibration factor K was 0.001 ohm per dial division. For mixes IIIA and IIIB the potentiometer resistance was equal to 50K and for all subsequent mixes, 500K. The circuit was adjusted so that when the probe resistance R_p was equivalent to zero the values of R_1 and R_2 were 234.9 ohms and 246.0 ohms respectively; at this setting the balance resistance was 10.970 ohms, or (10970 dial divisions)(0.001 ohm per microinch) where 0.001 ohm per microinch represented 492 dial divisions, and thus K was equal to one microinch. The variable resistance units, of which there were two (one a potentiometer and one a decade), provided a network of resistance for desensitizing the probe. The potentiometer was a Helipot Corp. instrument of 10,000 ohm capacity; the decade resistance units consisted of Shallcross Company models 820 and 840. Figure 2 illustrates a typical assembly of units.

Probe model No. 1 is shown in Figure 3. The brass rods, which extended 3.62 in. beyond the lower surface of the 0.25-in. thick cross-arm, were of 0.375-in. diameter brass rod and 6.25 in. apart at the conical tips. Waterproof tape was wrapped around the junction of the 12.25-in. long handle (comprised of 1.00-in. diameter Lucite tubing having a wall thickness of 0.06 in.) and the 6-in. long cross-arm (comprised of a 0.50 in. wide Lucite bar) to preclude entry of neat cement or cleansing water. The weight of this probe was 0.25 lb, including the rubber-insulated No. 20 wire leads.

Probe model No. 2, shown in Figure 4, employed 1.00-in. square brass plates in lieu of pointed rods. The plates, exposed faces of which were 4.00 in. beneath the underside of the cross-arm, were embedded in an epoxy resin; each capsulation was approximately 1.38 in. square and 0.75 in. thick and was integral with the semi-elliptical 0.62-in. diameter Lucite tube through which passed the conductor leads. The handle stem was about 16 in. long and comprised of Lucite bar stock 1.00 in. wide by 0.38 in. thick; the lower end constituted the cross-arm and, by means of acrylic cement, was fixed to the tubulure. A suitable slot in the tubulure, adjacent to the handle stem, provided the outlet for the rubber-insulated #20 wire leads. The gross weight of this probe was 0.94 lb.

The reason for changing to this probe style was recognition of the possibility that mixing water might collect along the upper and lower faces of the cross-arm of probe No. 1 (see Figure 5). With probe No. 2

this was impossible because immersion did not cover the connecting cross-arm as in probe No. 1.

In the case of the direct-current electrical resistance method the freshly mixed cement paste (or mortar or concrete) serves as the electrolyte relative to the metallic probe; due to electrochemical action, the paste function is similar to that of electrolyte in a storage battery. The proprietary version of the S. G. Tester involves a two-electrode probe wherein direct current oscillates the probe by means of a make-and-break-contact type of vibrator. Passing direct-current through the probe causes hydrogen (from the mixing water) to be released around one electrode; in effect, the gas serves as insulation around the electrode and the electrical resistance observed seemingly increases as a result. The hydrogen remains at one electrode continually unless the direct current is reversed, in which event hydrogen is dissipated at the first electrode and re-collected around the second electrode.

With the alternating-current resistance method the battery effect is either absent or present, depending upon the cycle phase. With this method there can be no hydrogen production. During the first half of the cycle the gas is created around the first electrode and during the second half of the cycle, around the second electrode, at which time the electrochemical action tends to eliminate hydrogen at the first electrode. If the proprietary S. G. Tester, together with its vibrating probe, were to operate with alternating current, the entire circuitry would require redesign; even so, high contact resistance of the probe and low resistance of the cement paste would negate any advantages possible with the alternating-current resistance method.

Contact resistance is the key to the explanation and implies an appreciable quantity of paste molecules in contact with the probe. When measuring small changes in resistance this effect always poses problems. If the paste is vibrated, the probe contact is improved although still far from ideal. If the voltage is increased, a heating effect is produced. If the paste resistance were high, e.g., thousands of ohms magnitude, contact resistance would be negligible. Variations in electric signal cause a shift in magnitude and all unwanted signals are "noise." For example, regardless of whether the concrete mixer were of 3- or 9-cu yd capacity, the effectiveness of a very small button-type probe or one wherein the electrodes were several feet apart would be doubtful as the "noise" would make repeatable observations impossible.

The power loss method and the induction conductivity method involve no probe. Therefore these methods are not encumbered with the problem of battery effect of the cement paste, nor hydrogen effects, nor probe contact-resistance effects.

Power Loss Method

This method operates on the principle of radio frequency (RF) attenuation, i.e., any change in W/C of the cement paste is reflected as an impedance change, voltage change, or amperage change in radiant energy emanating from an antenna-like source. The method involves not less than a 10,000-cycle alternating current to insure continuous wave (CW) propagation. The RF voltage output used in three experiments was 0.3 volt and decibel (db) readings indicated changes in electric power level. Maximum transmissible power available in the first experiment corresponded to a reading of 88 db; this level occurred when two turns of the conductor passed through a current transformer (built at the Laboratory) and when the acrylic container was not connected; with the specimen container connected the maximum level attainable was 75 db. Figure 6 shows a typical setup of the apparatus. The transformer cores were in contact and the entire unit encapsulated in thermosetting resin.

Subsequent experiments were conducted with slight variations of the power loss method. In the second experiment the transformer remained as in the first power loss experiment. In the third experiment the transformer cores were separated 1.5 in. by an acrylic spacer and the entire assembly encapsulated in synthetic rubber cured at room temperature.

In all three experiments with power loss, the instrument arrangement was similar. In the first and second, the signal generator was a Measurement Corporation model 82 and the field intensity meter a Stoddart Co. model NM20B; in the third, the only change in measurement instrument was the use of a Ferris Instrument Co. model 32B field intensity meter. In both the second and third experiments, field intensity was 98 db when a single turn of No. 14 copper wire was looped through the transformer.

Induction Conductivity Method

This method permits the measurement of electric current induced in the cement paste (or mortar or concrete). The method is based upon the principle that the cement paste sample serves as a conductive loop in coupling two transformer coils. Figure 7 illustrates the schematic of the sensing element and Figure 8 is a photograph of the external appearance of the sensing device and control instrument manufactured by Industrial Instruments Inc. Two iron-core toroidal windings are coaxially encapsulated in the Bakelite sensor. The longitudinal and transverse holes in the toroidal sensor, as well as the space intervening between the sensor exterior and the sample container, become filled with cement paste as the sensor is plunged into the mass of paste previously placed in the acrylic container. The sample thus effectively serves as a single-turn winding that links the magnetic circuits of the voltage and current transformers. There is no electrode problem because there is no contact between cement paste and metal. When a 20-volt 18,000-cycle alternating current is applied across the first toroid, the current in the second toroid depends upon the resistance of the cement-paste loop since the path through the toroid functions as a one-turn coupling of a transformer. The amount of electric current in the loop through the hole and through the paste surrounding the toroid depends upon the diameter and length of the opening and upon the conductivity of the paste within and around that opening. The current in the paste is measurable by means of the second toroid. The instrument circuit incorporates an automatic temperature compensation device. Calibration of the apparatus is easily accomplished by inserting a loop of wire through the toroid holes and then connecting in series with a decade resistance box.

The induction conductivity apparatus, illustrated in Figure 8 and manufactured by Industrial Instruments Inc., was comprised of three basic assemblies, namely, a transmitter, the conductivity cell, and a receiver. The transmitter consisted of an oscillator operating at 18 kc and a power amplifier. The conductivity cell has been described above. The receiver, in essence, was a sensitive vacuum tube voltmeter. The single dial knob was rotated, after the cell immersion in the paste, and the conductivity in ohms read directly from the dial indicator.

The induction conductivity apparatus was modified subsequently and a Wheatstone bridge sensing feature added to the circuitry. This allowed the instrument to be more sensitive to W/C changes. Nevertheless, as is apparent in Table XIII, the modification did not result in any perceptible improvement.

CEMENT PASTE

Constituents

All portland cement used in this task was type I manufactured by Riverside Cement Co. at its Crestmore Division, Riverside, Calif. All mixing water was fresh tap, bottled and stored at temperatures ranging between 71 and 76F. The bagged cement was stored in air-tight 55-gal drums until one week before use; as needed, one bag at a time was emptied into an air-tight 30-gal steel container and stored in the same room as the bottled water.

Mixing Apparatus

All mixing was accomplished with Hobart mixers. Except for series V, all mixes were produced using the model C-10 mixer equipped with 10-qt stainless steel bowl; series V mixes were produced in a 5-qt stainless steel bowl operated in the model N-50 mixer.

Upon completion of mixing, series III, IV, V, VIII, IX, X, and XI mixes were transferred into crocks preparatory to instrumental readings (see Figure 2). Mixes of series XII and XIV likewise were transferred into an acrylic cylinder (1.88 in. diameter by 10.0 in. high inside dimensions) equipped with an electrical jack; mixes of series XIII, XV, XVI, and XVII were transferred into an acrylic pan (6.44 in. diameter by 2.0 in. high inside dimensions) also equipped with a jack; refer to Figure 6. Mixes of series XVIII through XXIV were transferred into an acrylic cylinder (6 in. diameter by 12 in. high) upon completion of mixing.

Mixing Sequence

Except for mixes of series IX through XI, all mixes were mixed 3 minutes, allowed to rest (uncovered) 3 minutes, and remixed 3 minutes. Series IX mixes were mixed 3 minutes and rested 6 minutes. Series X mixes were mixed 6 minutes and rested 3 minutes. Series XI mixes were mixed 9 minutes and not rested. Excluding series IX, X, and XI, all mixing sequence was in conformity with ASTM test method C305-59T modified as per the latter half of section 4(b) of ASTM test method C243-58T.

DATA ANALYSIS

Alternating-Current Resistance Method

The chemical reaction between cement and water begins upon mixing and continues long after final set has occurred. The electrical resistance of fresh cement paste obviously is less at high W/C than at low W/C. The resistance increases with age as the products of cement hydration continue to develop during the early period prior to initial set. Tables I through IX indicate that such trends are not evident when the electrical flow is alternating current.

A statistical analysis of the test data was accomplished by G. E. Hayo of the Mathematics Group of the Laboratory's Physics and Mathematics Division and by R. L. Stearman of CEIR Inc., Los Angeles, Calif. Among the facts established, the more important are as follows:

1. Though the W/C range contemplated for field use extends from 0.25 to 0.95 (by weight), and considering the limitations of time and materials available for experimentation, the range investigated (0.40 to 0.60) meets the main objective as it contains those values critical to determining the usefulness of the method.

2. The coefficient of variation indicates that the alternating-current method involves a small measurement error (1.28 percent) when testing cement pastes which incorporate W/C ranging from 0.40 to 0.60 (by weight).

3. The inter-relation between age, W/C, and alternating-current resistance of the cement paste is quadratic. This effect restricts the use of the method inasmuch as two or more W/C may result in identical readings of the instrument.

4. Resistance, measured by the alternating-current method, increases as the cement paste grows older (based upon a maximum age, at observation, of 23 minutes).

5. The resistance values of cement paste differ appreciably according to the mixing sequence.

6. A significant decrease in resistance occurs when the cement paste is tested in a vitrified clay vessel instead of in a stainless steel vessel.

7. The size of metallic mixing bowl influences the resistance indicated by the alternating-current method, regardless of whether the cement paste is tested subsequently in the metallic bowl or in a crock.

In view of the above facts, subsequent experimentation with the power loss method and the induction conductivity method involved: (1) a specific mixing sequence, (2) a specific type and size mixing bowl, (3) specific ages at time of measurement, and (4) a range in W/C extending from 0.25 to 0.95 (by weight).

Power Loss Method

Table X reveals why this method is considered unsatisfactory for detecting variations in W/C. Regardless of whether the W/C was 0.40 or 0.60, the instrumental readings were practically identical.

Induction Conductivity Method

Table XI, XII, and XIII illustrate that this method is insufficiently sensitive to small changes in W/C when used with the components designed by Industrial Instruments Inc. The method does not reflect W/C changes having a magnitude of 0.10 or less.

When the commercial version of the apparatus is modified by incorporating a Wheatstone bridge sensing device, the resultant improvement in sensitivity is insignificant as is evident in Table XIII. Furthermore, in the case of the mix XXII series, the test data are incongruent insofar as reflecting changes in W/C are concerned.

CONCLUSIONS

1. The reliability of the 1000-cycle alternating-current resistance method is not as good as that of the direct-current resistance method which is employed in the proprietary version of the S. G. Concrete Mix Tester.

2. The power loss method is considered unsatisfactory for the purpose of corroborating small changes in W/C.

3. The induction conductivity method at best is considered satisfactory for detection of W/C changes of 0.20 or greater.

4. Direct-current resistance measurements are worthwhile for detecting W/C discrepancies not less than ± 0.05 (by weight).

ACKNOWLEDGMENT

The author is grateful to Mr. A. H. Jackson, Electronic Development Technician, for fabricating the special probes employed with the electric power loss method. Mr. Jackson's familiarity with the various electronic components was of considerable benefit in developing the test data.

Table I: Mix IIIA (W/C = 0.60) with Clamped Probe No. 1 in 1-gal Crock

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance* (ohms)
3.0	19.195	+8.225
3.5	19.198	+8.228
4.5	19.200	+8.230
5.5	19.202	+8.232
17.0	19.200	+8.230
17.5	19.200	+8.230
18.5	19.200	+8.230
19.5	19.200	+8.230
31.0	19.200	+8.230
31.5	19.200	+8.230
32.5	19.200	+8.230
33.5	19.200	+8.230
46.0	19.200	+8.230
46.5	19.200	+8.230
47.5	19.200	+8.230
48.5	19.200	+8.230

*(Total Resistance)-(Probe Resistance) = Paste Resistance with regard to algebraic signs. Probe Resistance = 10.970 ohms (by shortcircuiting test set).

Table I: Mix IIIB (W/C = 0.50) with Clamped Probe No. 1 in 1-gal Crock

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance* (ohms)
3.0	19.200	+8.230
3.5	19.200	+8.230
4.5	19.200	+8.230
5.5	19.200	+8.230
**	---	---

* Probe Resistance = 10.970 ohms (by shortcircuiting test set). Fixed probe frame cross-arm 1 in. below paste surface. Normal immersion 0.5 in. for all mixes of series involving alternating-current resistance.

**Further readings impossible becauseof insufficient sensitivity (of instrument) to change in paste resistance.

Table I: Mix IIIC (W/C = 0.40) with Clamped Probe No. 1 in 2-gal Crock

Satisfactorily accurate readings were not possible with this mix.

Table II: Mix IVA (W/C = 0.60) with Clamped Probe No. 1 in 1-gal Crock

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance* (ohms)
3.0	10.950	-0.020
3.5	11.090	+0.120
4.5	11.200	+0.230
5.5	11.300	+0.330
8.0	11.280	+0.310
8.5	11.440	+0.470
9.5	11.560	+0.590
10.5	11.630	+0.660
13.0	11.460	+0.490
13.5	11.530	+0.560
14.5	11.600	+0.630
15.5	11.680	+0.710
18.0	11.450	+0.480
18.5	11.470	+0.500
19.5	11.570	+0.600
20.5	11.630	+0.660
23.0	11.720	+0.750
23.5	11.750	+0.780
24.5	11.820	+0.850
25.5	11.880	+0.910
28.0	12.090	+1.120
28.5	12.115	+1.145
29.5	---	---
30.5	12.260	+1.290
33.0	11.950	+0.980
33.5	12.090	+1.120
34.5	12.150	+1.180
35.5	12.200	+1.230
38.0	12.000	+1.030
38.5	12.030	+1.060
39.5	12.115	+1.145
40.5	12.180	+1.210
120.0	13.170	+2.200**

* Probe Resistance = 10.970 ohms (by shortcircuiting test set)
**Hand-held probe whereas all other reading with clamped probe.

Table II: Mix IVB (W/C = 0.50) with Clamped Probe No. 1 in 1-gal Crock

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance* (ohms)
3.0	9.640	-1.330
3.5	9.870	-1.100
4.5	10.120	-0.850
5.5	10.310	-0.660
8.0	10.420	-0.550
8.5	10.560	-0.410
9.5	10.730	-0.240
10.5	10.860	-0.110
12.0	10.605	-0.365
12.5	10.700	-0.270
13.5	10.815	-0.155
14.5	10.920	-0.050
16.0	10.315	-0.655
16.5	10.375	-0.595
17.5	10.540	-0.430
18.5	10.640	-0.330
20.0	10.940	-0.030
20.5	11.050	+0.080
21.5	11.150	+0.180
22.5	11.225	+0.255
24.0	11.260	+0.290
24.5	11.380	+0.410
25.5	11.510	+0.540
26.5	11.560	+0.590
28.0	11.595	+0.625
28.5	11.710	+0.740
29.5	11.810	+0.840
30.5	11.870	+0.900
33.0	11.510	+0.540
33.5	11.610	+0.640
34.5	11.705	+0.735
35.5	11.755	+0.785
83.0	11.850	+0.880**

* Probe Resistance = 10.970 ohms (by shortcircuiting test set).
**Probe hand-held whereas all other readings with probe clamped.

Table II: Mix IVC (W/C = 0.40) with Clamped Probe No. 1 in 2-gal Crock

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance* (ohms)
4.0	13.360	+2.390
4.5	13.565	+2.595
5.5	13.630	+2.660
6.5	13.715	+2.745
8.0	13.630	+2.660
8.5	13.710	+2.740
9.5	13.825	+2.855
10.5	13.890	+2.920
12.0	13.500	+2.530
12.5	13.630	+2.660
13.5	13.750	+2.780
14.5	13.825	+2.855
16.0	13.820	+2.850
16.5	13.950	+2.980
17.5	14.090	+3.120
18.5	14.145	+3.175
20.0	14.235	+3.265
20.5	14.320	+3.350
21.5	14.345	+3.375
22.5	---	---
24.0	14.030	+3.060
24.5	14.190	+3.220
25.5	14.320	+3.350
26.5	14.400	+3.430
28.0	14.010	+3.040
28.5	14.145	+3.175
29.5	14.240	+3.270
30.5	---	---
33.0	14.215	+3.245
33.5	14.305	+3.335
34.5	14.350	+3.380
35.5	14.400	+3.430

*Probe Resistance = 10.970 ohms (by shortcircuiting test set).

Table III: Mix VA (W/C = 0.60) with Clamped Probe No. 1 in 1-gal Crock

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance* (ohms)
1	---	---
2	-5.790	-16.760
3	-4.560	-15.530
4	-4.310	-15.280
5	-4.100	-15.070
6	-3.880	-14.850
7	-3.710	-14.680
8	-3.565	-14.535
9	-3.440	-14.410
10	-3.320	-14.290
11	-3.220	-14.190
12	-3.140	-14.110
13	-3.070	-14.040
14	-3.000	-13.970
15	-2.940	-13.910
16	-2.880	-13.850
17	---	---
18	-2.885	-13.855
19	-2.780	-13.750
20	-2.740	-13.710
21	-2.680	-13.650
22	-2.640	-13.610
23	-2.575	-13.545
24	-2.540	-13.510
25	-2.250	-13.220

*Difference between Total Resistance and Probe Resistance, regardless of algebraic sign. Probe Resistance = 10.970 ohms (by shortcircuiting test set).

Table III: Mix VB (W/C = 0.50) with Probe Clamp No. 1 in 1-gal crock

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance* (ohms)
1	---	---
2	-5.685	-16.655
3	-5.390	-16.360
6	-4.760	-15.730
8	---	---
9	---	---
10	-4.270	-15.240
11	-4.180	-15.150
12	-4.110	-15.080
13	-4.040	-15.010
14	-3.980	-14.950
15	-3.920	-14.890
16	-3.870	-14.840
17	-3.770	-14.740
18	-3.710	-14.680
19	-3.690	-14.660
20	-3.675	-14.645
21	-3.645	-14.615
22	-3.600	-14.570
23	-3.570	-14.540
24	-3.570	-14.540
25	-3.570	-14.540

*Probe Resistance = 10.970 ohms (by shortcircuiting test set).

Table III: Mix VC (W/C = 0.40) with Clamped Probe No. 1 in 2-gal Crock

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance* (ohms)
1.5	-3.220	-14.190
2	-2.880	-13.850
3	-2.680	-13.650
6	-2.340	-13.310
8	-2.165	-13.135
9	-2.105	-13.075
10	-2.040	-13.010
12	-1.950	-12.920
13	-1.900	-12.870
14	-1.870	-12.840
15	-1.825	-12.795
24	-1.350	-12.320

*Probe Resistance = 10.970 ohms (by shortcircuiting test set).

Table III: Mix VD (W/C = 0.40) with Clamped Probe No. 1 in 2-gal Crock*

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance** (ohms)
1	---	---
2	-3.360	-14.330
3	-3.320	-14.290
6	-2.910	-13.880
12	-2.290	-13.260
24	-1.765	-12.735
25	-1.720	-12.690

* Duplicate test of Mix VC.
**Probe Resist ıce = 10.970 (by shortcircuiting test set).

Table IV: Mix VIA (W/C = 0.60) with Clamped Probe No. 1 in 5-qt bowl*

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance** (ohms)
1	-0.740	-11.710
2	-0.610	-11.580
3	-0.535	-11.505
4	-0.450	-11.420
5	-0.360	-11.330
6	-0.295	-11.265
7	-0.215	-11.185
8	-0.150	-11.120
9	-0.055	-11.025
10	+0.040	-10.930
11	+0.100	-10.870
12	+0.155	-10.815
13	+0.220	-10.750
14	+0.260	-10.710
15	+0.345	-10.625
16	+0.430	-10.540
17	+0.490	-10.480
18	+0.550	-10.420
19	+0.590	-10.380
20	+0.665	-10.305
21	+0.700	-10.270
22	+0.725	-10.245
23	+0.745	-10.225
24	+0.750	-10.220
25	+0.590	-10.380a/

*Insufficient immersion, due to bowl size, resulted in upper 0.5 in. of probe frame cross-arm being exposed.
a/Very doubtful.

Table IV: Mix VIB (W/C = 0.50) in 5-qt Bowl

No observations were made with this mix because probe was not fully immersed in cement paste.

Table IV: Mix VIC (W.C = 0.40) in 5-qt Bowl

No observations were made with this mix because probe was not fully immersed in cement paste.

Table V: Mix VIIA (W/C = 0.60) with Clamped Probe No. 1 in 10-qt Bowl

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance* (ohms)
1	0.520	-10.450
2	0.550	-10.420
3	0.630	-10.340
4	0.705	-10.265
5	0.780	-10.190
6	0.840	-10.130
7	0.910	-10.060
8	0.970	-10.000
9	1.050	-9.920
10	1.115	-9.855
11	1.185	-9.785
12	1.240	-9.730
13	1.290	-9.680
14	---	---
15	1.370	-9.600
16	1.400	-9.570
17	1.440	-9.530
18	1.475	-9.495
19	1.510	-9.460
20	1.540	-9.430
21	1.580	-9.390
22	1.605	-9.365
23	1.635	-9.335
24	1.680	-9.290
25	1.880	-9.090

*Probe Resistance = 10.970 ohms (by shortcircuiting test set).

Table V: Mix VIIB (W/C = 0.50) with Clamped Probe No. 1 in 10-qt Bowl

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance* (ohms)
1	1.180	-9.790
2	1.160	-9.810
3	1.165	-9.805
4	1.190	-9.780
5	1.215	-9.755
6	1.260	-9.710
7	1.310	-9.660
8	1.370	-9.600
9	1.425	-9.545
10	1.480	-9.490
11	1.525	-9.445
12	1.550	-9.420
13	1.580	-9.390
14	1.610	-9.360
15	1.640	-9.330
16	1.670	-9.300
17	1.690	-9.280
18	1.720	-9.250
19	1.740	-9.230
20	1.770	-9.200
21	1.800	-9.170
22	1.810	-9.160
23	1.820	-9.150
24	1.840	-9.130
25	2.350	-8.620

*Probe Resistance = 10.970 ohms (by shortcircuiting test set).

Table V: Mix VIIC (W/C = 0.40) with Clamped Probe No. 1 in 10-qt Bowl

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance* (ohms)
1	---	---
2	---	---
3	3.480	-7.490
4	3.570	-7.400
5	3.610	-7.360
6	3.650	-7.320
7	3.690	-7.280
8	3.720	-7.250
9	3.750	-7.220
10	3.780	-7.190
11	3.810	-7.160
12	3.840	-7.130
13	3.870	-7.100
14	3.900	-7.070
15	3.920	-7.050
16	3.940	-7.030
17	3.970	-7.000
18	3.990	-6.980
19	4.000	-6.970
20	4.020	-6.950
21	4.040	-6.930
22	4.060	-6.910
23	4.070	-6.900
24	4.080	-6.890
25	4.080	-6.890

*Probe Resistance = 10.970 ohms (by shortcircuiting test set).

Table VI: Mix VIIIA (W/C = 0.60) with Clamped Probe No. 2 in 10-qt Bowl

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance* (ohms)
1	---	---
2	2.720	-8.250
3	3.200	-7.770
4	3.910	-7.060
5	4.610	-6.360
6	5.150	-5.820
7	5.670	-5.300
8	6.070	-4.900
9	6.400	-4.570
10	6.660	-4.310
11	6.910	-4.060
12	7.120	-3.850
13	7.310	-3.660
14	7.490	-3.480
15	7.640	-3.330
16	7.800	-3.170
17	7.940	-3.030
18	8.070	-2.900

*Probe Resistance = 10.970 ohms (by arbitrarily setting instrumentation to obtain same factor as with first probe).

Table VI: Mix VIIIB (W/C = 0.50) with Clamped Probe No. 2 in 10-qt Bowl

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance* (ohms)
1	---	---
2	1.150	-9.820
3	2.250	-8.720
4	2.890	-8.080
5	3.380	-7.590
6	3.720	-7.250
7	3.970	-7.000
8	4.220	-6.750
9	4.490	-6.480
10	4.730	-6.240
11	5.030	-5.940
12	5.110	-5.860
13	5.240	-5.730
14	5.350	-5.620
15	5.490	-5.480
16	5.620	-5.350
17	5.770	-5.200
18	5.890	-5.080

*Probe Resistance = 10.970 ohms (by arbitrarily setting instrumentation to obtain same factor as with first probe).

Table VI: Mix VIIIC (W/C = 0.40) with Clamped Probe No. 2 in 10-qt Bowl

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance* (ohms)
1	---	---
2.5	3.520	-7.450
3	4.170	-6.800
4	4.900	-6.070
5	5.290	-5.680
6	5.550	-5.420
7	5.740	-5.230
8	5.920	-5.050
9	6.110	-4.860
10	6.260	-4.710
11	6.430	-4.540
12	6.630	-4.340
13	6.750	-4.220
14	6.890	-4.080
15	7.040	-3.930
16	7.180	-3.790
17	7.300	-3.670
18	7.440	-3.530

*Probe Resistance = 10.970 ohms (by arbitrarily setting instrumentation to obtain same factor as with first probe)

Table VII: Mix IXA (W/C - 0.60) with Clamped Probe No. 2 in 10-qt Bowl

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance* (ohms)
1	---	---
2	3.960	-7.010
3	4.590	-6.380
4	4.760	-6.210
5	4.890	-6.080
6	5.020	-5.950
7	5.140	-5.830
8	5.380	-5.590
9	5.600	-5.370
10	5.970	-5.000
11	6.050	-4.920
12	6.060	-4.910
13	6.130	-4.840
14	6.160	-4.810
15	6.260	-4.710
16	6.350	-4.620
17	6.430	-4.540
18	6.550	-4.420

*Probe Resistance = 10.970 ohms (by arbitrarily setting instrumentation to obtain same factor as with first probe).

Table VII. Mix IXB (W/C = 0.50) with Clamped Probe No. 2 in 10-qt Bowl

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance* (ohms)
1	---	---
2	3.180	-7.790
3	3.440	-7.530
4	3.740	-7.230
5	3.900	-7.070
6	4.070	-6.900
7	---	---
8	4.200	-6.770
9	4.340	-6.630
10	4.480	-6.490
11	4.620	-6.350
12	5.070	-5.900
13	5.240	-5.730
14	5.280	-5.690
15	5.180	-5.790
16	5.170	-5.800
17	5.180	-5.790
18	5.200	-5.770

*Probe Resistance = 10.970 ohms (by arbitrarily setting instrumentation to obtain same factor as with first probe).

Table VII: Mix IXC (W/C = 0.40) with Clamped Probe No. 2 in 10-qt Bowl

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance* (ohms)
1	---	---
2.5	4.940	-6.030
3	5.190	-5.780
4	5.620	-5.350
5	5.960	-5.010
6	6.250	-4.720
7	6.560	-4.410
8	6.710	-4.260
9	6.850	-4.120
10	7.010	-3.960
11	7.150	-3.820
12	7.230	-3.740
13	7.390	-3.580
14	7.520	-3.450
15	7.650	-3.320
16	7.770	-3.200
17	7.900	-3.070
18	8.030	-2.940

*Probe Resistance = 10.970 ohms (by arbitrarily setting instrumentation to obtain same factor as with first probe).

Table VIII: Mix XA (W/C = 0.60 with Clamped Probe No. 2 in 10-qt Bowl

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance* (ohms)
1	---	---
2.5	5.180	-5.790
3	5.710	-5.260
4	6.110	-4.860
5	6.280	-4.690
6	6.490	-4.480
7	6.710	-4.260
8	6.920	-4.050
9	7.060	-3.910
10	---	---
11	7.280	-3.690
12	7.410	-3.560
13	7.540	-3.430
14	7.710	-3.260
15	7.770	-3.200
16	---	---
17	---	---
18	8.080	-2.890

*Probe Resistance = 10.970 ohms (by arbitrarily setting instrumentation to obtain same factor as with first probe).

Table VIII: Mix XB (W/C = 0.50) with Clamped Probe No. 2 in 10-qt Bowl

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance* (ohms)
1	---	---
2	4.520	-6.450
3	4.940	-6.030
4	5.140	-5.830
5	5.260	-5.710
6	5.440	-5.530
7	5.560	-5.410
8	5.680	-5.290
9	5.800	-5.170
10	5.970	-5.000
11	6.060	-4.910
12	6.180	-4.790
13	6.260	-4.710
14	6.360	-4.610
15	6.460	-4.510
16	6.560	-4.410
17	6.630	-4.340
18	6.700	-4.270

*Probe Resistance = 10.970 ohms (by arbitrarily setting instrumentation to obtain same factor as with first probe).

Table VIII: Mix XC (W/C = 0.40) with Clamped Probe No. 2 in 10-qt Bowl

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance* (ohms)
1	---	---
2	4.960	-6.010
3	5.350	-5.620
4	5.650	-5.320
5	5.890	-5.080
6	6.070	-4.900
7	6.220	-4.750
8	6.360	-4.610
9	6.420	-4.550
10	6.540	-4.430
11	6.710	-4.260
12	6.800	-4.170
13	6.900	-4.070
14	7.020	-3.950
15	7.130	-3.840
16	7.250	-3.720
17	7.400	-3.570
18	7.420	-3.550

*Probe Resistance = 10.970 ohms (by arbitrarily setting instrumentation to obtain same factor as with first probe).

Table IX: Mix XIA (W/C = 0.60) with Clamped Probe No. 2 in 10-qt Bowl

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance* (ohms)
1	---	---
2.5	6.870	-4.100
3	7.200	-3.770
4	7.570	-3.400
5	7.740	-3.230
6	7.880	-3.090
7	8.030	-2.940
8	8.140	-2.830
9	8.250	-2.720
10	8.360	-2.610
11	8.450	-2.520
12	8.540	-2.430
13	8.610	-2.360
14	8.660	-2.310
15	8.700	-2.270
16	8.750	-2.220
17	8.800	-2.170
18	8.820	-2.150

*Probe Resistance = 10.970 ohms (by arbitrarily setting instrumentation to obtain same factor as with first probe).

Table IX: Mix XIB (W/C = 0.50) with Clamped Probe No. 2 in 10-qt Bowl

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance* (ohms)
1	---	---
2.5	5.450	-5.520
3	5.720	-5.250
4	6.100	-4.870
5	6.240	-4.730
6	6.350	-4.620
7	6.480	-4.490
8	6.630	-4.340
9	6.900	-4.070
10	---	---
11	7.030	-3.940
12	7.120	-3.850
13	7.210	-3.760
14	7.240	-3.730
15	7.270	-3.700
16	7.360	-3.610
17	7.620	-3.350
18	7.740	-3.230

*Probe Resistance = 10.970 ohms (by arbitrarily setting instrumentation to obtain same factor as with first probe.

Table IX: Mix XIC (W/C = 0.40) with Clamped Probe No. 2 in 10-qt Bowl

Paste Age (Minutes)	Total Resistance (ohms)	Paste Resistance* (ohms)
1	---	---
2.5	5.600	-5.370
3	5.770	-5.200
4	6.100	-4.870
5	6.280	-4.690
6	6.470	-4.500
7	6.630	-4.340
8	6.800	-4.170
9	6.910	-4.060
10	7.030	-3.940
11	7.140	-3.830
12	7.260	-3.710
13	7.420	-3.550
14	7.560	-3.410
15	7.670	-3.300
16	7.770	-3.200
17	7.900	-3.070
18	8.000	-2.970

*Probe Resistance = 10.970 ohms (by arbitrarily setting instrumentation to obtain same factor as with first probe.

Table X: Power Loss

Mix	W/C	Paste Age (Minutes) at Test Start	Paste Age (Minutes) at Test End	Instrument Reading (decibels) at Test Start	Instrument Reading (decibels) at Test End
XIIA	0.60	2.0	5.0	96.5	96.5
XIIC	0.40	1.0	5.0	96.5	96.5
XIIIA	0.60	1.0	5.0	90.0	90.0
XIIIC	0.40	1.0	5.0	90.0	90.0
XIVA	0.60	1.5	5.0	96.5	96.5
XIVC	0.40	1.0	5.0	96.5	96.5
XVA	0.60	1.0	5.0	89.5	89.5
XVC	0.40	1.0	5.0	89.0	89.0
XVIA	0.60	0.25	15.0	72.0	72.0
XVIC	0.40	0.33	16.0	71.0	71.5
XVIIA	0.60	1.25	16.25	40.0	50.0
XVIIC	0.40	1.5	16.5	51.0	51.0

Table XI: Induction Conductivity

Mix	W/C	Paste Age (Minutes) at Test Start	Paste Age (Minutes) at Test End	Conductivity (ohms) at Test Start	Conductivity (ohms) at Test End
XVIIIA	0.60	1	10	13	10
XVIIIB	0.50	1	10	10	10

Table XII: Induction Conductivity*

Mix	W/C	Conductivity (ohms) of cement paste at age 1 min	2 min	3 min	4 min	5 min	10 min	15 min
XIXA	0.60	13	14	14	15	15	15	16
XIXB	0.50	14	13	13	14	15	15	16
XIXC	0.40	15	15	15	16	16	16	17
XXA	0.95	15	15	15	15	15	15	16
XXC	0.25	--	3	3	3	3	3	3
XXIA	0.85	13	13	13	13	13	13	13
XXIC	0.35	--	9	9	9	10	10	10

*Using Industrial Instruments Inc. apparatus calibrated by the manufacturer.

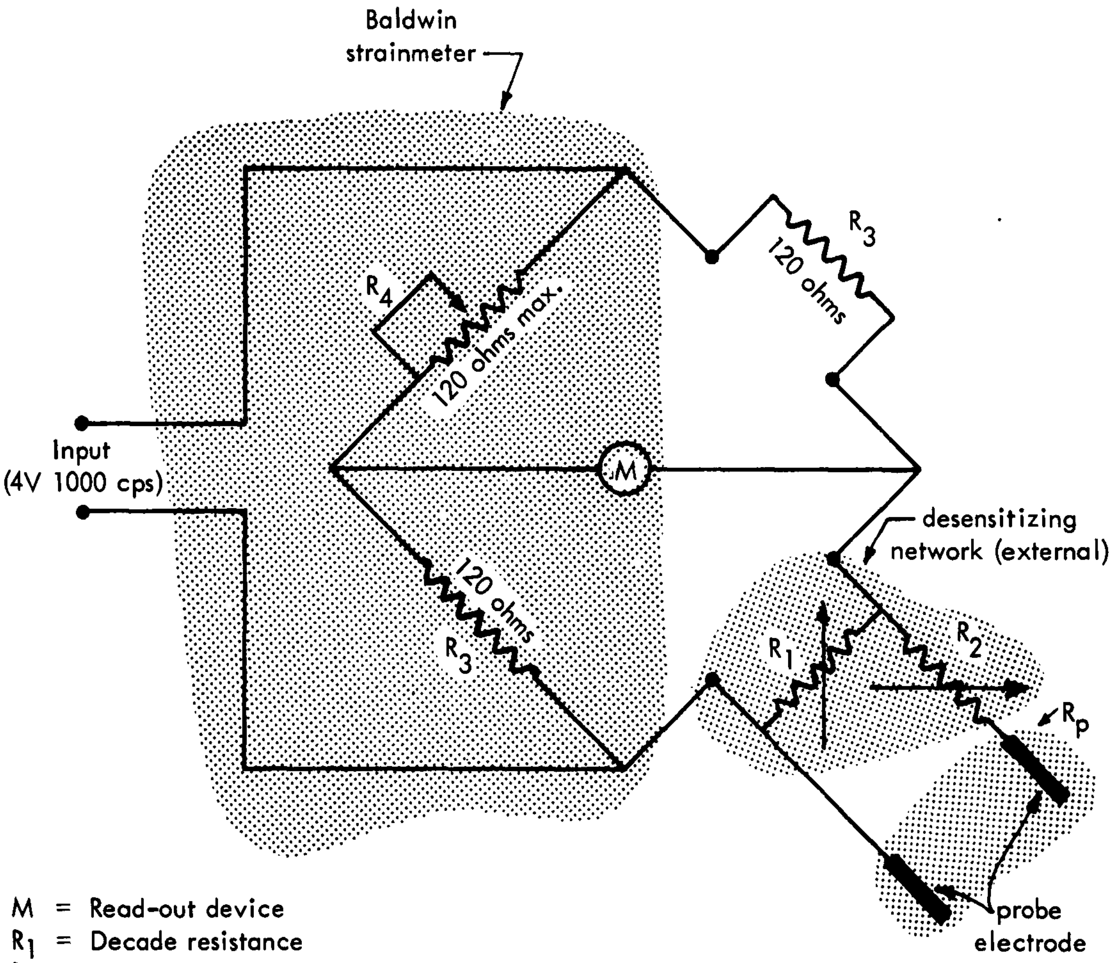
Table XIII: Induction Conductivity*

Mix	W/C	Induction Conductivity (volts·10^{-6}) of cement paste at age 1 min	2 min	3 min	4 min	5 min	10 min	15 min
XXIIA	0.60	--	5850	5820	5747	5756	5806	5822
XXIIB	0.50	--	9626	9654	9700	9736	9905	10052
XXIIC**	0.40	--	7470	7340	7346	7360	7435	7537
XXIIIA	0.95	6057	5852	5600	5520	5550	5620	5660
XXIIIC***	0.25	--	--	--	--	6410	6805	6878
XXIVA	0.85	8700	8661	8761	8783	8790	8903	8946
XVIVC**	0.35	--	8760	8830	8880	8914	9125	9265

* Using Industrial Instruments Inc. apparatus modified by a Wheatstone bridge sensing device.

** Transverse hole in cell exposed 0.25 in. above paste surface.

***Paste required hand-packing into holes in cell and thus readings at early ages were impossible.



M = Read-out device
R_1 = Decade resistance
R_2 = Potentiometer
R_3 = Internal fixed arm of bridge
R_4 = Internal variable arm of bridge
R_p = Resistance of cement paste across the electrodes

Figure 1. Basic circuit in alternating-current resistance method.

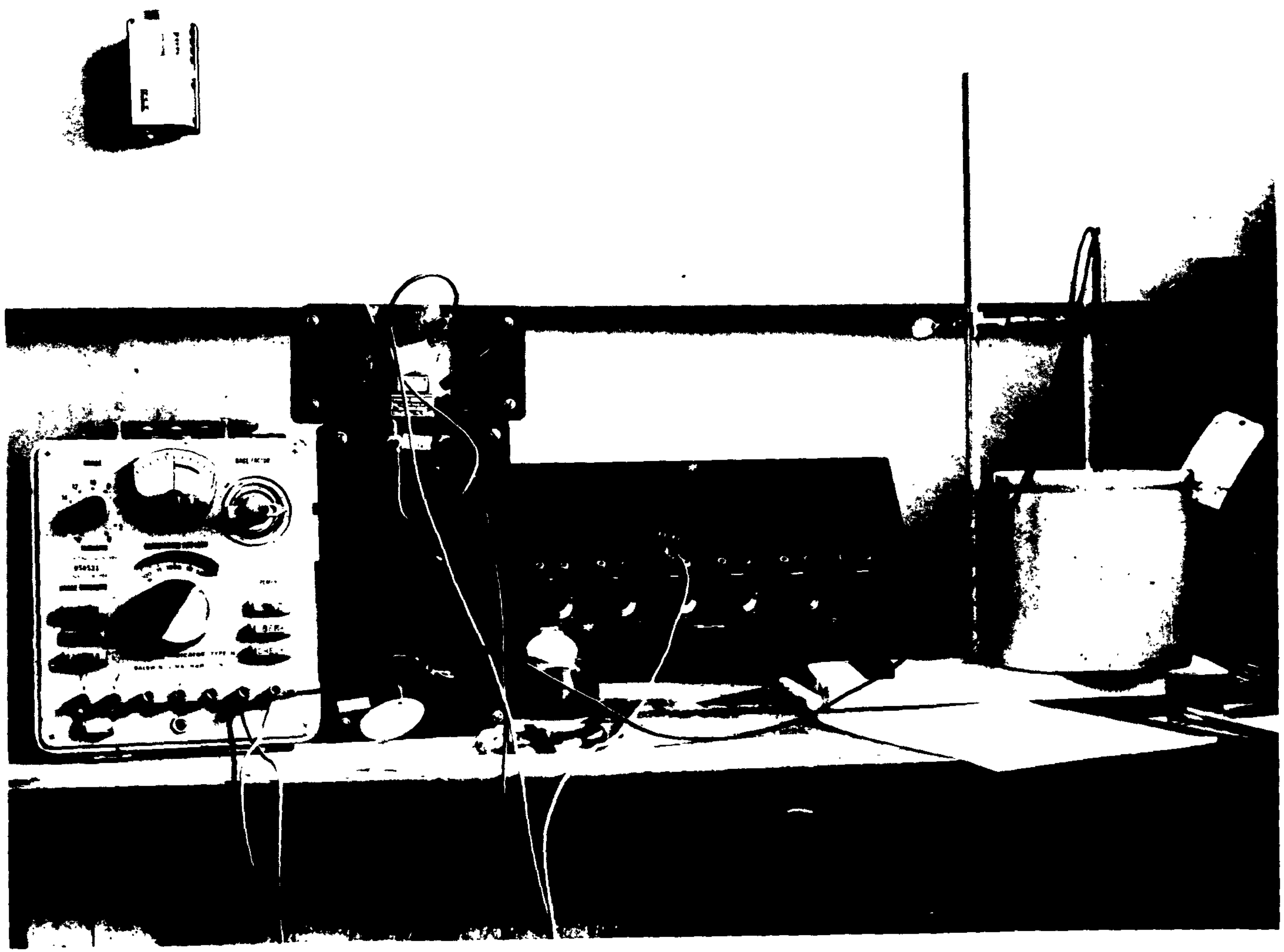


Figure 2. Alternating-current resistance method. Typical setup with crock as specimen container.

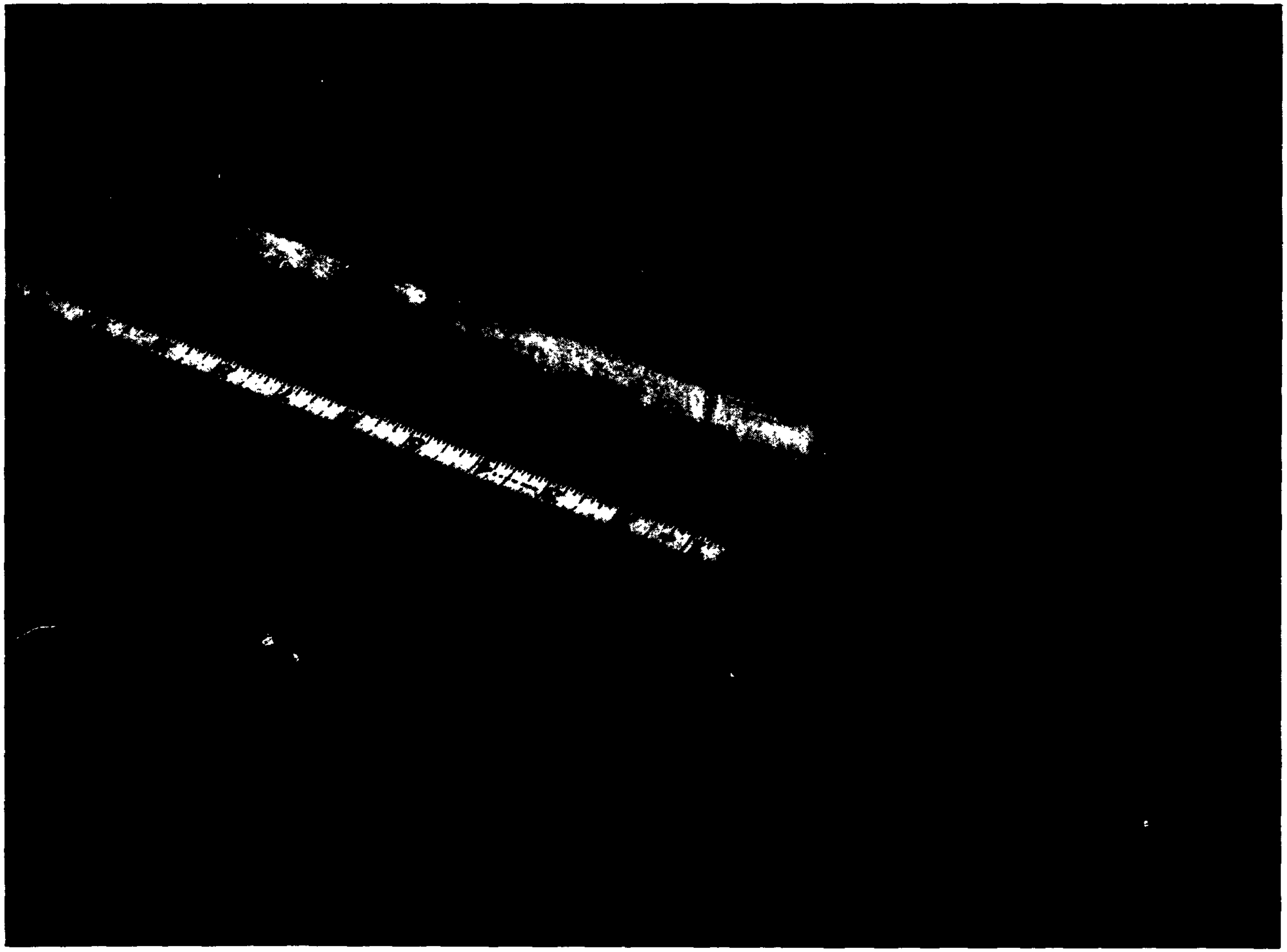


Figure 3. Probe No. 1 employed with alternating-current resistance method.

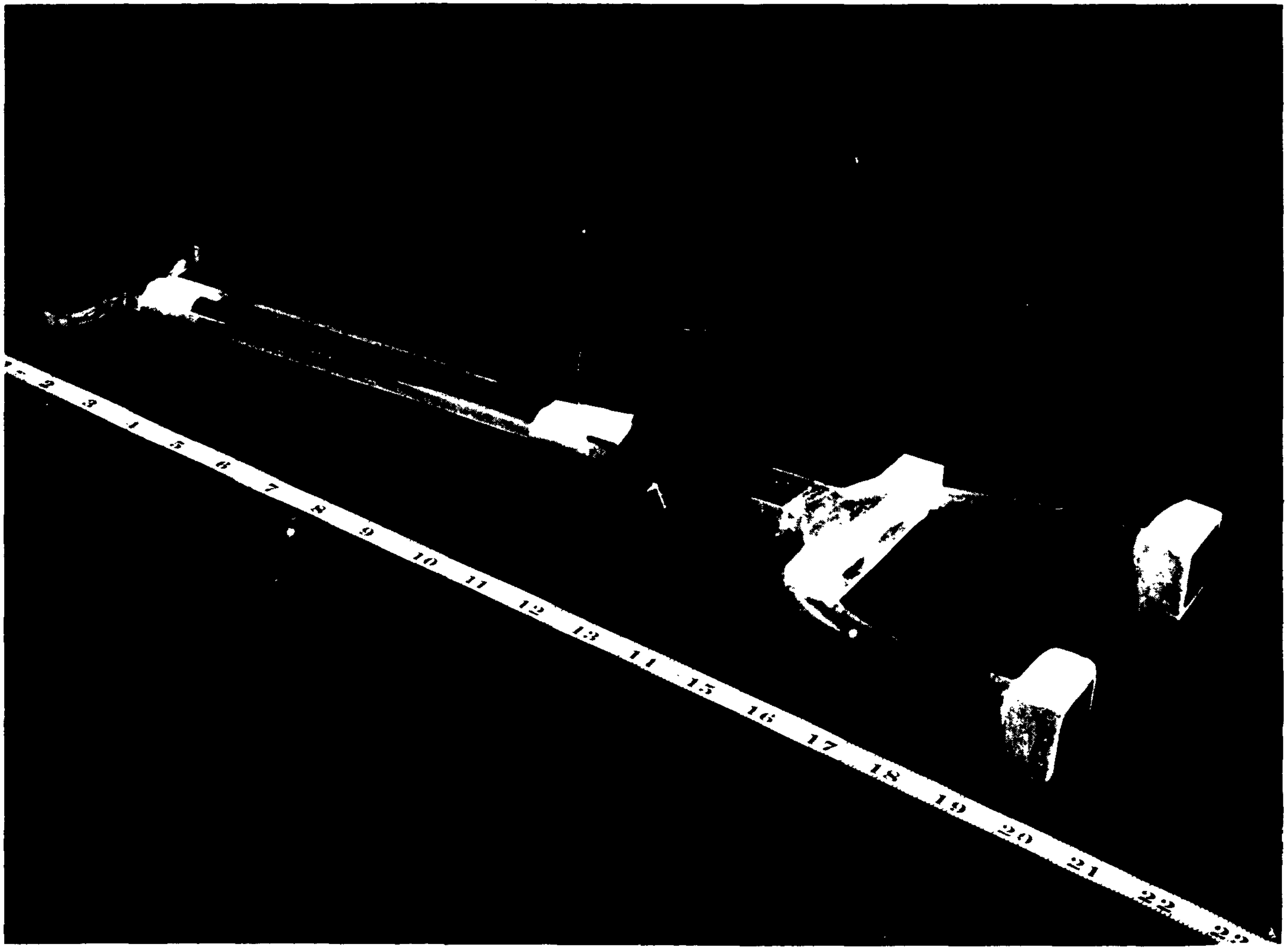


Figure 4. Probe No. 2 employed with alternating-current resistance method.

Figure 5. Alternating-current resistance method. Typical setup with probe No. 1 and stainless steel mixing bowl.

Figure 6. Typical setup for power loss method. Acrylic pan being filled with paste (W/C = 0.40). Acrylic cylinder in background. Relative sizes indicated by 12-in. scale attached to front edge of bench.

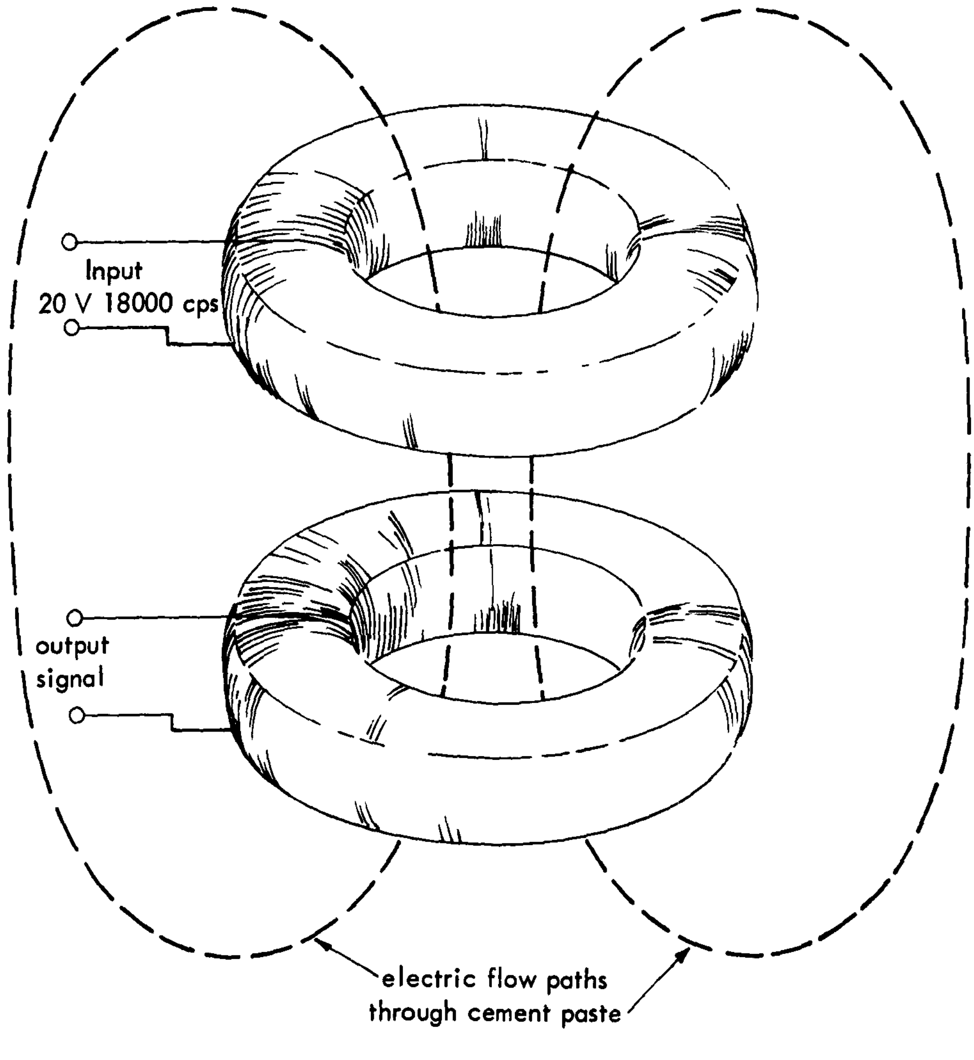


Figure 7. Simplified schematic of toroids in sensing cell.

Figure 8. Induction conductivity sensing cell and control instrument. Relative sizes indicated by 6-in. scale in foreground.